A Case Study of the Failure on Apollo 13

Based on TMX-65270, Report of Apollo 13 Review Board

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ABSTRACT

The dramatic journey of the crippled Apollo 13 vehicle has been heavily documented and popularized. Many people know there was an explosion in the service module which caused the vehicle to lose its oxygen supply. Less well known is the set of circumstances which led to the explosion. This paper examines the manufacturing, processing and testing history of oxygen tank #2, detailing the additive effects which caused the oxygen to ignite and to overpressure the tank.

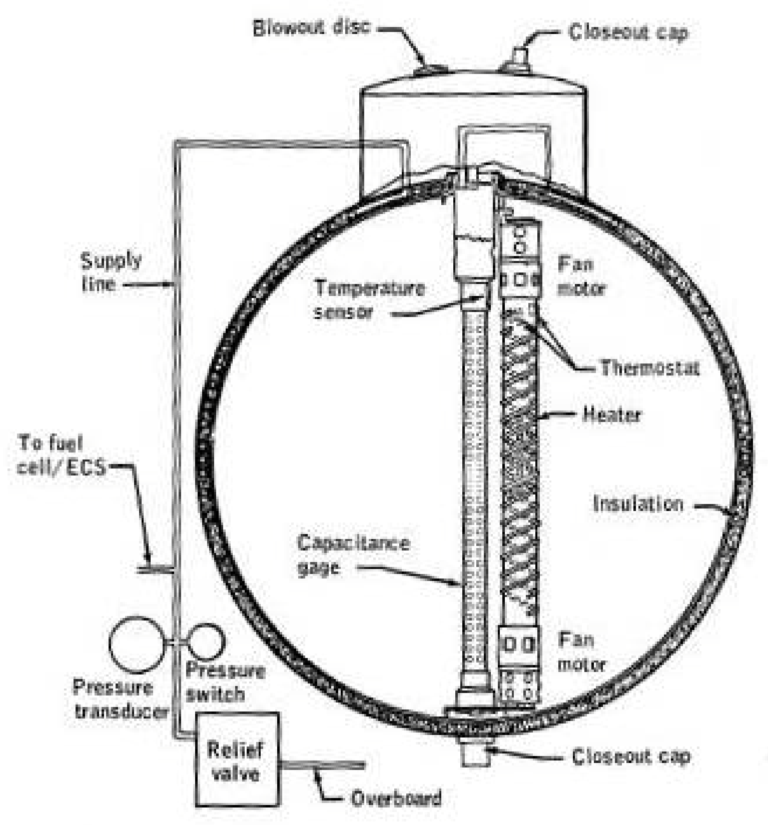
The Apollo 13 Flight

Apollo 13 was to be the third manned lunar landing. The selected landing site was in the hilly uplands of the Fra Mauro lunar region. A scientific package of five experiments was to be emplaced on the lunar surface. Also, the landing crew was to gather a third set of selenological samples from the lunar surface to be studied by scientists on earth. However, on the third flight day, an explosion of oxygen tank 2 in bay 4 of the Service Module (SM) changed the scientific exploration flight into an outstanding rescue mission.

Design of the Apollo Oxygen Tank Assembly

The oxygen tank of the Apollo Service Module (SM) is constructed of concentric inner and outer shells, containing a vacuum between shells to reduce heat leak. A dome caps the tank providing containment for the fluid, electrical and signal paths into and out of the tank. See figure 1.

Figure 1 Service Module Oxygen Tank



The gap between the tank shells also contains insulating material. Two tubular assemblies, the heater tube and the quantity probe, are located inside the tank. The heater tube assembly encloses two thermostatically protected heater coils, as well as two fans to stir oxygen in the tank, which is necessary in a zero gravity environment. The quantity probe assembly has a capacitance gauge in the lower half which electronically measures oxygen level in the tank. The probe consists of an inner cylinder to serve as fill and drain tube, and also as one plate of the capacitance gauge. On the upper half of the probe a temperature sensor is mounted near the head. Wiring for the assembly's electrical elements is routed out of the tank into the dome. There the wiring combines with a connector which links to circuitry to the command module (CM) and the service module (SM).

The routing of wiring and lines from the tank to the tank dome is shown in Figure 2.

Figure 2 Wiring and Lines between Oxygen Tank and Dome

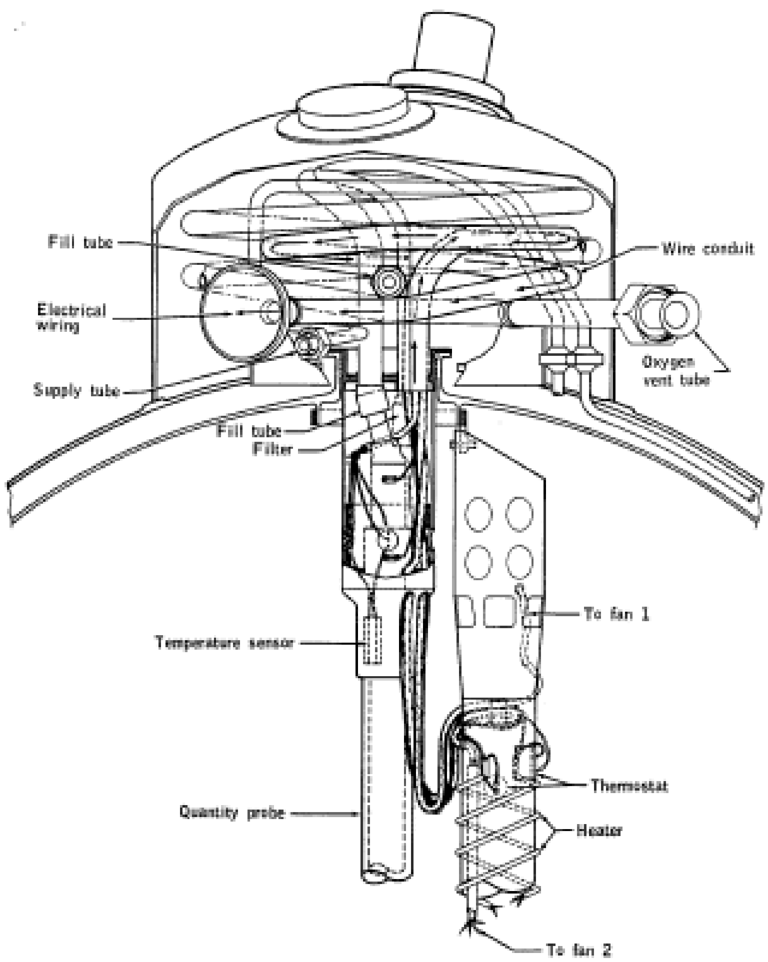
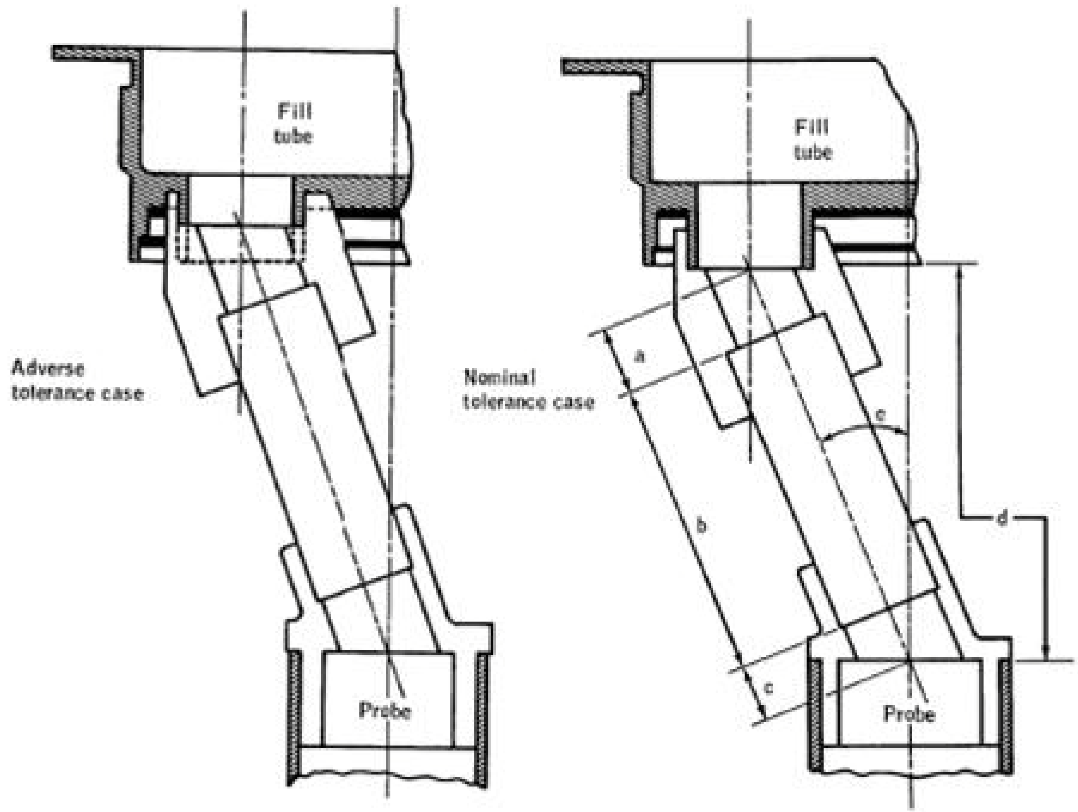


Figure 4-2.- Oxygen tank wiring and lines.

The fill line outside the oxygen tank enters, connecting to the inner cylinder of the capacitance gauge via a coupling comprised of Teflon adapters and Inconel tubing. The dimensions and tolerances for the assembly were chosen such that if worst case deviations occurred so the coupling didn't extend from fill line to gauge cylinder, a very loose fit would ensue. See Figure 3.

Figure 3 Nominal and Adverse Coupling Tolerance Cases



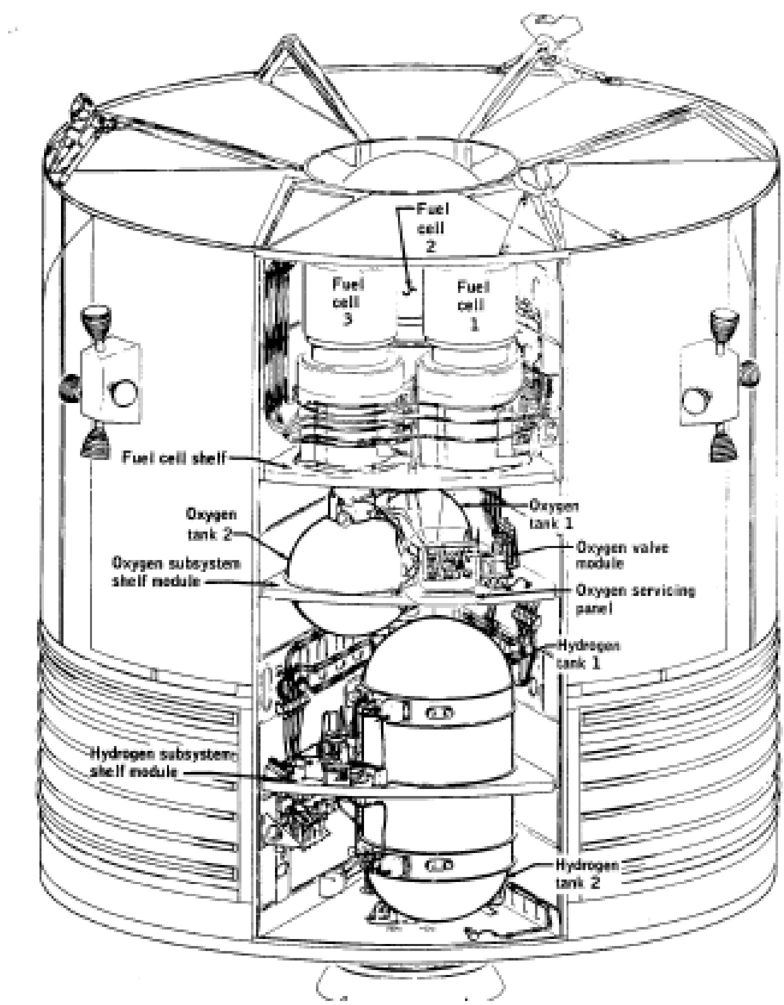
The oxygen supply line travels from the head of the quantity probe into the dome, supplying oxygen to the fuel cells in the SM and the environmental control system (ECS) of the CM. The supply line includes a relief valve. In nominal operation, the tank pressure is measured by gauge in the supply line, and a pressure switch at the gauge powers on the heaters if the pressure drops below a pre-selected value. Heat is added to the tank to preserve oxygen pressure at a level which is sufficient to provide oxygen on demand as tank quantity decreases during flight.

The tank is designed to operate at 320 pounds of supercritical oxygen at pressures from 865 to 935 pounds per square inch absolute (psia). (Supercritical means that the oxygen is kept at a temperature and pressure to maintain a homogeneous, single-phase fluid.) Initially the tank is filled with liquid oxygen at -297° F and is operational in the range -340° to 80° F.

The oxygen tank design has a burst pressure of 2200 psia at -150° F, over twice the nominal operating pressure for that temperature. The relief valve releases oxygen outboard if pressure reaches 1000 psi. The tank dome is open to the vacuum maintained between tank shells and has a rupture disk which erupts at 75 psi.

Oxygen tanks 1 and 2 are mounted on a shelf in bay 4 of the service module as show in Figure 4.

Figure 4 Arrangement of Cryogenic Systems and Fuel Cells in SM Bay 4



Manufacturing History of the Oxygen Tank Assembly

The inner shell of the tank was manufactured by Airite Products Division of Electrada Corporation under subcontract to Beech Aircraft Corporation. The quantity probe was made by Simmonds Precision Products, Inc. The fans and fan motors were made by Globe Industries, Inc. Manufacture of oxygen tank 2 began in 1966. It was the eighth block II tank built by Beech, which had previously produced 28 block I tanks.

The tank shells are manufactured as an upper hemisphere and a lower hemisphere. After the halves are joined, the tubular assemblies are placed through the top opening. Bolting and wiring occurs through this opening, affording limited access and visibility. Possible damage to wire insulation is not easily detected before the tank is capped and welded.

Several minor manufacturing flaws were uncovered during testing of oxygen tank 2. There was porosity in a weld on the lower half of the outer shell, which was ground and re-welded. Incorrect welding wire had been used for a weld on a vacuum pump mounted on the tank dome; this was re-welded. The upper fan motor extracted excessive current and made unwarranted noise and so was replaced. These repairs required disassembly of the tank. The heater assembly tube was replaced, which included new heaters and fans. The tank was re-assembled and re-sealed. The inter-tank space was pumped down during a 28 day period to create the necessary vacuum.

Oxygen Tank Testing at Beech Aircraft Corporation

Acceptance testing of the oxygen tank included extensive dielectric, insulation and functional tests of the heaters, fans, and vacuum ion pumps. Leak tests were performed at 500 psi and the proof test at 1335 psi; both tests incorporated helium.

After testing, the tank was filled with liquid oxygen for proof testing at 1335 psi using the tank heaters powered by 65 volts ac (V ac). Heat leak testing lasted 25-30 hours using oxygen at 900 psi over a wide range of ambient conditions and out-flow rates. At test completion, about 100 pounds of oxygen remained in the tank. Seventy-five pounds were vented from the tank through the supply line at a controlled rate. The tank was emptied of the rest of the oxygen by applying warm gas at 30 psi to the vent line to expel the oxygen out the fill line. No difficulties or anomalies were noted during de-tanking.

Acceptance testing established that the heat leak rate into the tank was greater than allowable by specification. After reworking (the nature of the rework is unspecified in failure analysis report) the heat leak rate improved but was still above that allowable by specification. A formal waiver was submitted and accepted for the tank to be used “as is”. Some other minor flaws were accepted, none of which were considered serious and the details are not included in the failure analysis report. The bolt holes in the support for the electrical plug in the tank dome were oversized. The heater assembly had an oversized rivet hole above the lower fan. After acceptance, oxygen tank 2 was filled with helium at 5 psi and shipped to North American Rockwell on 3 May 1967.

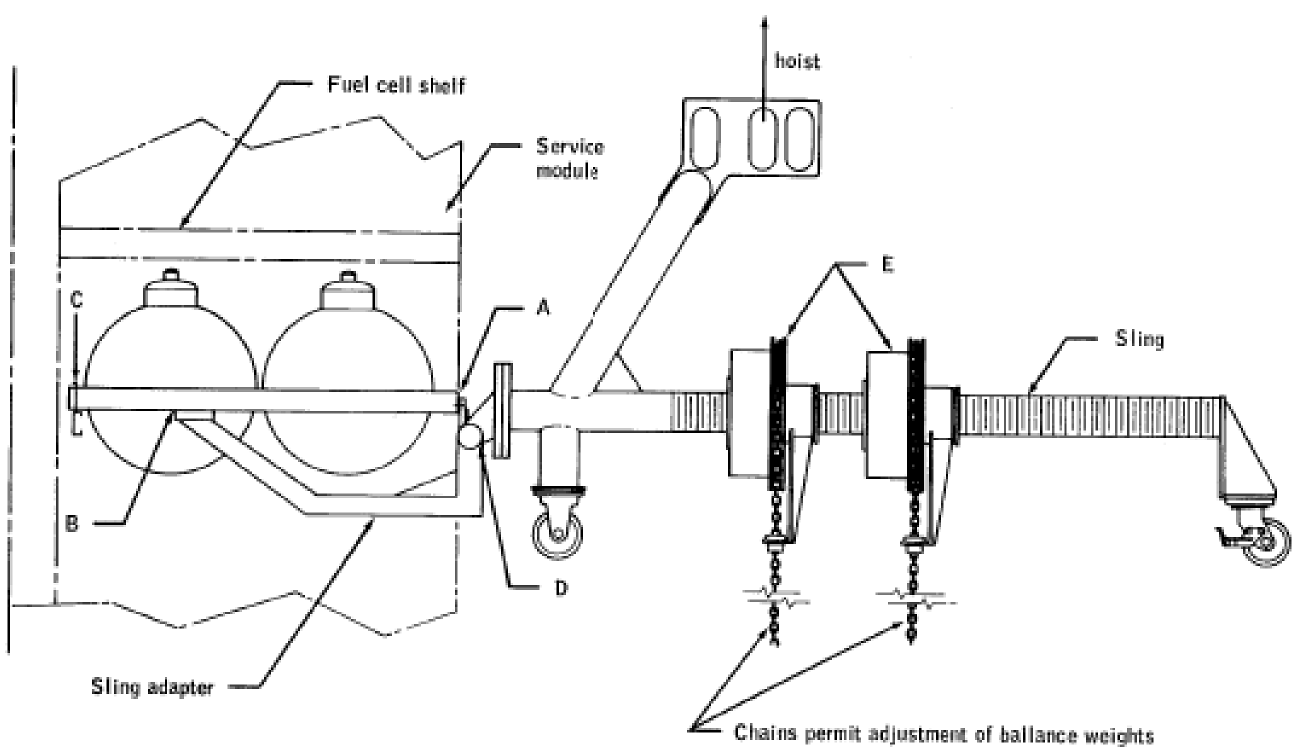
Assembly and Testing of the Oxygen Tank at North American Rockwell

Beech oxygen tank serial number 10024XTA0009, oxygen tank 1, and tank serial number 10024XTA0008, oxygen tank 2, were used in the assembly of oxygen shelf serial number 0632AAG3277. The shelf was completed at North American Rockwell on 11 March 1968. This shelf was planned to be installed in SM 106 which would be flown on the Apollo 10 mission. The assembled shelf began testing on 27 April. The test sequence included proof-pressure, leak and functional assessments. A valve on the shelf had leaked during testing and was repaired. No other anomalies were recorded for oxygen tank 2. Therefore no repair work was performed on the tank at North American Rockwell (NA). None of the testing at NA used lox in the tanks.

On 4 June 1968, the oxygen shelf was installed in SM 106. During 3-8 August the shelf was tested as part of the SM assembly. No anomalies were recorded.

Electromagnetic interference had been recorded on earlier Apollo spacecraft, which was caused by the vacuum-ion pumps on the cryogenic tank domes. A design modification eliminated the anomaly. Since the oxygen shelf assembly in SM 106 contained the problematic pumps, it was decided to replace the assembly. The oxygen shelf was removed on 21 October for modification.

Figure 5 Hoist and Sling Arrangement for Shelf Assembly



The hoist and sling assembly shown in Figure 5 was used in removal of the oxygen shelf from SM 106. Disconnections were finished and a fitting from the crane was placed under the shelf to lift and remove it from the SM bay. A shelf bolt had been mistakenly left in the assembly. Consequently after the shelf was raised about two inches, the crane fixture broke and the shelf fell back into place. Photographs of the assembly following the mishap indicated that the close out cap of oxygen tank 2 might have struck the underneath side of the fuel cell shelf during the incident. At the time of the incident engineers thought that the shelf had simply dropped into place and they performed calculations to estimate the resultant force from the fall. After deliberation, the engineers decided that the shelf was initially accelerated upward before dropping which agreed with the photographic evidence.

The accident was recorded. The remaining bolt was removed and the shelf detached without additional problem. Because of this incident the oxygen shelf was re-tested for integrity, which including leak tests, proof-pressure test, and functional tests of pressure transducers, switches, thermal switches, and vacuum-ion pumps. No cryogenic testing was performed at this point. Additional visual inspection revealed no other problems. It should be noted that these tests would not have discovered any fill line leakage in oxygen tank 2. Additional tests and calculations performed during post-flight investigation concluded that the forces on the shelf during drop were likely close to those calculated at the time of the event. The investigating board determined the probability of tank damage from this accident was low, but it is possible that a loosely fitting fill tube might have become displaced by the drop.

The oxygen shelf passed post-accident testing and was installed in SM 109 on 22 November 1968. Standard post-shelf installation testing was performed after installation (the same testing which was done when the shelf was installed in SM 106). No significant problems were noted in the test history. Service module 109 was shipped to Kennedy Space Center (KSC) in June, 1969.

Testing at Kennedy Space Center

The SM was mated to CM in the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC). The assembly passed testing with nothing unusual recorded concerning oxygen tank 2, and the Saturn V vehicle was moved to the launch pad on 16 December 1969.

A countdown demonstration test (CDDT) began on 16 March 1970. During CDDT the oxygen tanks were emptied to a pressure of 5 millimeters of mercury and then filled with oxygen to 80 psi and the fuel cells were cooled. When the cells had reached the necessary temperature, cryogenic oxygen loading began. The oxygen tanks were filled to 331 psi. This process happened without anomaly. Generally during CDDT the oxygen tanks are partially emptied to 50% capacity as part of test. Oxygen tank 1 performed as expected. However, oxygen tank 2 only emptied to 92% capacity. Emptying the tanks employs routing gaseous oxygen at 80 psi through the vent line while keeping the fill line open. This did not reduce the oxygen amount in tank 2. The engineering test team proceeded with CDDT to completion and then examined the dilemma more closely. An Interim Discrepancy Report (IDR) was written about the incident which was reassigned to a Ground Support Equipment (GSE) discrepancy report. At that point a GSE filter was alleged as cause for the detanking failure.

A dialogue was held with KSC, Manned Spaceflight Center (MSC), NA, and Beech personnel concerning the behavior of oxygen tank 2. After this, de-tanking recommenced on 27 March. Oxygen tank 2 had, in the elapsed time before de-tanking was resumed, self-pressurized to 178 psi and was 83% full. The tank was vented through the fill line. Now the quantity was 65%. Supplementary discussion among KSC, MSC, NA, and Beech personnel suggested that the de-tanking difficulty might be due to a leak in the line between quantity probe and fill line because of the loose fit between tube and sleeve. A leak in that line would allow gaseous oxygen to leak into the fill line, not driving lox from the tank. (Refer to Figure 2.) A discrepancy report was written for the oxygen subsystem.

A routine de-tanking test was performed on both oxygen tanks which pressurized the tanks through the vent lines while opening the fill lines. Oxygen tank 1 emptied in minutes; tank 2 did not. Using higher pressure oxygen did not empty the tank. A decision was made to try to boil off the residual oxygen using the oxygen tank heaters. The heaters were connected to the GSE power supply of 65 V dc. After one and a half hours of heating, the fans were turned on to assist the movement of oxygen out of the tank. After six hours the tank was at 35%. The next step taken to empty the tank was pressure cycling. The fans and heaters were left on and the tank was pressurized to 300 psi and held for a few seconds. (The precise time is not specified.) Then the tank was vented through the fill line. The initial pressure cycle emptied an additional 7% of oxygen, so the process was repeated. The tank emptied after five cycles. After eight hours of operation, the heaters and fans were finally powered off.

Kennedy Space Center personnel still supposed a loose fitting fill line connection to the quantity probe inner cylinder was the cause of the de-tanking problem. They conferred with MSC and NA, and the group decided to see if now the oxygen tank would fill without problem. If the tube was loose, it could cause a short in flight, but this short would not generate enough heat to cause problems. The group chose this for flight rationale if the tank passed the fill test.

To remove the oxygen tank shelf from the SM and replace it would be difficult and time consuming, needing 45 hours. Also, replacing the shelf offered a high probability of damaging or degrading other parts of the SM. So if there was good rationale to fly the shelf, it would not be replaced. On 30 March (twelve days before the launch of Apollo 13), personnel proceeded with the tank fill test. Time was still copious to replace the shelf if that choice were made.

In order to have comparison data from tank 1, both tanks were flow tested. Beech conducted a test to determine the energy that a short between the quantity probe plates would produce in the event such a short occurred. The test demonstrated a low energy level produced. (The exact energy level from this test is not provided in the failure report.) Both tanks were filled to 20% capacity on 30 March with no problems noted during filling. Tank 1 emptied as it had previously. However, tank 2 again required pressure cycling and heating to empty.

The Apollo project organization discussed the history of the tank as part of the launch decision, before the point of delay was reached. The shelf drop incident was not mentioned in these discussions. The de-tanking test at Beech was not discussed either because it was believed the procedure Beech used was different than the testing used by NA and KSC. In actuality, the final section of the Beech testing was quite similar, only using a slightly lower gox pressure.

These talks involved both technical and management personnel from KSC, MSC, NA, Beech and NASA headquarters. The main point of the discussions was a possibly loose fill tube and its potential impact. Effectively no consideration was given to the use of heaters and fans in oxygen tank 2, or to the extended time of operation. The only point made was that the fans and heaters did work during and after the de-tanking procedures. Most of the individuals in these discussions knew nothing of the fan and heater use or of the extended operation of both components. The ones who were aware did not consider any adverse consequences of the excess heat in the tank and so didn't advise their management of this.

Each heater has a thermostatic switch as protection against extreme heat. The switch should open if the temperature rises above 80° F. Switches which were tested as part of the failure investigation post-flight failed to open when the heaters used power from the 65 V dc GSE. This is the power used during the CDDT and tanking tests pre-Apollo 13 at KSC. The switches were rated at 28 V dc, which is the standard operating power for the Apollo craft, and did not operate correctly at 65 V dc. Qualification and testing procedures for the heater did not test the ability at any point for the switches to operate at 65 V dc. Data recorded during the CDDT and tanking test at KSC were reviewed post-flight. The data showed that the switches did not open at any time when the recorded temperature was above 80° F. Further testing during the post-flight failure investigation showed that the heaters, since they were not cut off by the thermostatic switch, may have reached temperatures as high as 1000° F during the detanking procedures. This greatly elevated temperature was shown to cause severe damage to Teflon insulation on wiring. Severe damage almost certainly occurred to the wiring inside oxygen tank 2 during the extended heater use.

This information was not available to decision makers at the time of the pre-launch discussions, instead virtually all attention focused on the potential of damage due a loose fill tube. The final decision left the oxygen shelf assembly in place on SM 109 and preparations for the launch of Apollo 13 began.

The Failure

From launch through the first 46 hours of flight, oxygen tank 2 performed without anomaly. At 46:40:02 mission elapsed time (MET), the crew, performing routine procedures, turned on the fans in oxygen tank 2. In three seconds, the oxygen quantity rose from an expected reading of 82% to an off-scale reading of over 100%. Post-flight analysis demonstrated this could have been caused either by a short circuit or an open circuit in the quantity gauge wiring or by a short circuit between the gauge plates. Events following the spike in pressure indicate that a short circuit between the plates was the more likely failure mode. The fans in oxygen tank 2 were powered on twice more with no adverse effects at 47:54:50 and 51:07:44 MET. However, the quantity gauge continued to read off scale.

At 55:52:30 ground elapsed time (GET), a master alarm in the CM caution and warning system advised low pressure in oxygen tank 1. Oxygen tank 1, which had not exhibited unusual or anomalous behavior through testing, had read below nominal operating pressure several times since launch.

Ground controllers were already busy trying to understand and diagnose the problem with oxygen tank 2. They were puzzling over why the oxygen quantity fluctuated so much and they were unable to get an accurate reading. To assist his troubleshooting, the electrical systems officer (EECOM) in Mission Control Center (MCC) requested for the crew to turn on the fans in both tanks to stir up the oxygen and compare the readings. The CM pilot acknowledged the request; telemtered data received in MCC indicated at 55:53:20 GET that current was applied to oxygen tank 2 fan motors.

At 55:54:53.555 GET, telemetry from the Apollo spacecraft was lost completely for 1.8 seconds. During this data drop-out, the spacecraft caution and warning system signaled that dc main bus B had a serious under volt (loss of power). Simultaneously the crew heard a loud bang from the spacecraft.

Events occurring between the power-on of the fans and the when the problem was apparent to the crew are covered in detail in Part 4, Chapter 4 of TMX-65270, Report of Apollo 13 Review Board. It is evident that wiring inside the oxygen tank had lost its Teflon insulation due to the overheating during the de-tanking procedures at KSC. When the fan-on request was performed, the current flow generated a spark which ignited oxygen in the tank. The tank was over-pressured by the explosion and burst, causing damage to adjacent systems, including oxygen tank 1, and blowing off the side panel covering SM bay 4. The damage to oxygen tank 1 caused a slow leak in the tank and/or its lines or valves. Photos of the SM taken by the crew at CM jettison showed a gap left by the missing panel, showed that the fuel cell shelf (above the oxygen shelf) was tilted, and that the high-gain antenna was damaged.

The loss of oxygen made using the fuel cells impossible. The CM had only battery power remaining, which was normally only used during re-entry. The only source of oxygen for the CM was a surge tank and the re-press tanks (for re-pressurizing CM after cabin venting). Thus the lunar module (LM) was the only source of sufficient oxygen and electricity to return the crew safety to the earth.

The CM landed in the Pacific Ocean on 17 April, bringing the crew home weary but safe. Also, on 17 April, Thomas O. Paine, NASA Administrator, issued a memo to Edgar Cortright, director of Langley Research Center, appointing him head of the Apollo 13 Review Board, charged with "reviewing the circumstances surrounding the incident, establishing probable cause(s) of the accident, assessing the effectiveness of flight recovery actions, reporting these findings, and developing recommendations for corrective or other actions". The Board issued their final report in NASA technical memorandum TMX-65270, Report of Apollo 13 Review Board, which served as primary source material for this case study.

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Acronyms

CDDT	Count Down Demonstration Test
gox	gaseous oxygen
GSE	Ground Support Equipment
IDR	Interim Discrepancy Report
KSC	Kennedy Space Center
lox	liquid oxygen

MCC	Mission Control Center
MSC	Manned Spacecraft Center
NA	North American Rockwell
NASA	National Aeronautics and Space Administration
psi	pounds per square inch
psia	pounds per square inch absolute
VAB	Vehicle Assembly Building
V ac	volts alternating current
V dc	volts direct current